

## Novel approaches to the control of salt damage

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*Conservation scientists at the Institute of Archaeology have a longstanding interest in how the growth of salt crystals damages ancient buildings, wall paintings and objects in museums. They are now participating in a European research consortium that is investigating novel methods of reducing salt damage. The Institute's role in the project is to assess how environmental conditions affect the process of salt damage and to examine how salt crystallization might be inhibited.*

Anyone who has visited Petra in Jordan will have been struck not only by the rock-cut tombs for which Petra is famous, but also by the severe deterioration from which some of the tombs are suffering (Fig. 1). The deterioration is caused in part by the growth of salt crystals within the pores of the rock. The salts, which are naturally present in the rock, repeatedly dissolve and crystallize under the influence of fluctuating temperature and atmospheric humidity. The rock cannot withstand the pressure of the growing crystals, and the surface gradually powders away.

One of the Institute's research students, Fadi Bala'awi, is looking at the effect of wind speed on decay rates at Petra. His research will show whether decay could be reduced through the provision of shelter, either natural or manmade. The Institute is also involved in a pan-European project, funded by the European Commission, that is investigating another approach to the control of salt damage, which could have worldwide application. Salt damage is not

unique to Petra; indeed, it is one of the main causes of decay in porous building materials such as stone, brick and unfired earth. It is responsible for severe damage to buildings and monuments throughout the world, and also to wall paintings, sculpture and museum objects.

### Salt crystallization

Salt crystallization takes place when the limit of saturation for a salt solution is exceeded. This is brought about in two main ways: through water evaporation, which leads to an increasingly concentrated solution, or through a fall in temperature, because the solubility of many salts decreases with temperature. But the process of crystallization is reversible. Under sufficiently humid conditions, salt crystals can deliquesce by taking up water vapour from the air to form a solution once again. Similarly, an increase in temperature can cause precipitated salt crystals to re-dissolve. Fluctuations in environmental conditions can thus cause repeated cycles of salt crystallization and deliquescence. As a result, salt damage is not usually caused by a single event. Instead, it is

frequently a continuing process that leads to far greater damage in the long term.

### Treatment options

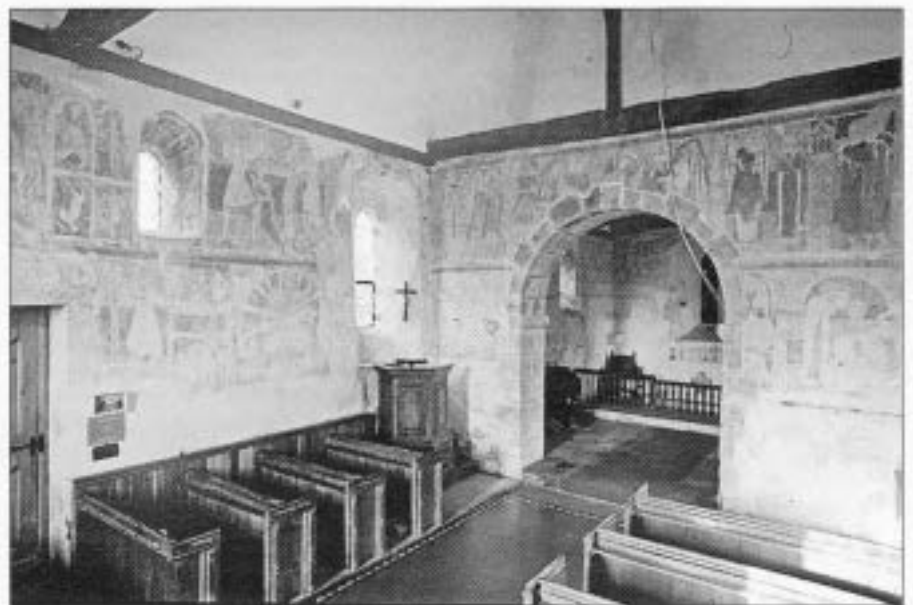
Salt damage presents a particularly difficult challenge for the conservator, not only because the mechanisms by which the damage occurs are still not fully understood, but also because the present options for treatment are extremely limited. One can opt for a policy of salt removal, in the hope that reducing the amount of salts present will reduce the rate of damage. However, it is impossible to remove all salts from monuments, masonry, large sculptures and wall paintings (Figs 2, 3). Indeed, it may be neither easy nor desirable to exclude the access of moisture to the object, which provides the means for mobilizing and transporting further salt. So, over time, salts have a tendency to re-accumulate. Moreover, under certain circumstances the selective removal of part of the salt system can lead to an increase in the rate of damage because of an alteration in the behaviour of the salts remaining after treatment. So, less salt does not always necessarily mean less damage. An alternative approach is to moderate the damaging behaviour of the salts, either by passive means or by direct treatment, and it is in these aspects of the problem that the Institute has been actively involved in new research.

### Environmental control

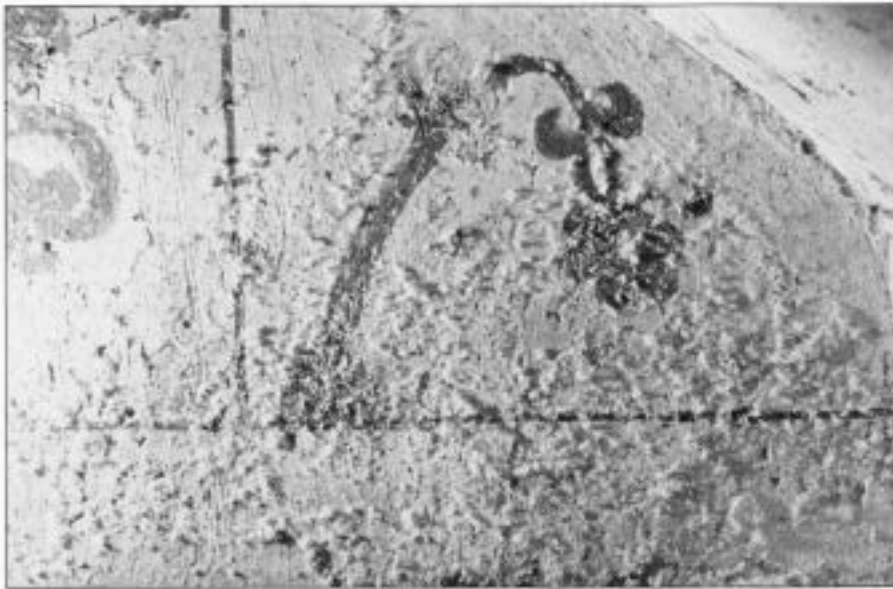
Changes in relative humidity (RH) and temperature play a key role in the activation of salt damage, and so environmental control has been increasingly cited as a desirable means of reducing salt deterioration, especially in wall paintings and museum objects.<sup>1,2,3</sup> However, this form of passive



**Figure 1** Rock-cut façade of a tomb at Petra, Jordan, showing severe salt damage along the base.



**Figure 2** The interior of the nave of Hardham Church, West Sussex, 1997. The twelfth-century wall paintings at Hardham form the most complete cycle of Romanesque wall paintings surviving in England. Sadly, they are in extremely poor condition, primarily because of the effects of salt crystallization.



**Figure 3** Detail of one of the wall-painting scenes in the nave of Hardham Church, 1997, showing severe disruption of the painted surface caused by salt crystallization.

amelioration is difficult to get right, and, like most conservation interventions, carries the risk that, if it is applied incorrectly, the damage to the object could be exacerbated. It is therefore very important that the environmental conditions selected to limit the salt damage are appropriate for achieving this end.

A significant recent advance in this area of research at the Institute has been the development of an environmental control of salts (ECOS) software program.<sup>4</sup> Other research, also undertaken at the Institute, has investigated the kinetics of salt behaviour to establish the timescale over which damage to wall paintings can take place, and the role that the various environmental, salt- and object-related factors play, in order to facilitate the application of environmental-control measures.<sup>5</sup> But, despite the advantages of environmental control as a passive form of treatment, in many situations (e.g. in the open air or when there are severe conflicts of building use) it is not a sufficient or indeed feasible means of preventing further damage. Another approach to the reduction of salt damage that has often been suggested, but remains as yet unrealized, is the use of crystallization inhibitors.

### The current European project

Crystallization inhibitors have a long history of use in industry, for example for the prevention of barite crystallization in offshore oil extraction processes, but their application in the field of conservation has not yet been fully explored. Therefore, a new project of the European Commission, with the acronym Saltcontrol, is currently being undertaken as part of the FP6 Sixth Framework Programme, to tackle this problem. The project, coordinated by the University of Ghent, aims to investigate the use of crystallization inhibitors as a direct

means of altering salt behaviour to prevent damage occurring.<sup>6</sup> The role of the Institute within the project is to assess the influence of environmental conditions on the process of salt damage, and to examine how this affects the inhibition efficiency of crystallization inhibitors under consideration.

### Influence of environmental conditions

At present there is a lack of general agreement concerning the exact mechanisms by which salts cause damage within porous materials, but there are strong arguments supporting the view that it is attributable to the development of crystal-growth pressures when the salt crystallizes from a supersaturated solution.

Salt-crystallization inhibitors are effective in delaying the onset of crystallization, allowing the solution to become progressively more supersaturated. Nevertheless, under conditions of continuing evaporation or if the temperature falls to sufficiently low levels, it is inevitable that, even in the presence of inhibitors, at some stage the system will start to crystallize. The amount of crystal-growth pressure generated has been related to the degree of supersaturation at which crystallization occurs.<sup>7</sup> Consequently, the use of inhibitors carries the risk that, if crystallization does take place, the solution will be more supersaturated than it would otherwise have been, and so greater damage could result. It is therefore most important to establish the limits of environmental tolerance under which inhibitors can be applied safely.

A key aspect of the role the environment plays in precipitating salt damage in culturally important buildings and objects is the fact that climatic conditions are not constant. Levels of RH and temperature

undergo significant variation, resulting in cycles of salt dissolution and re-crystallization. In this way, changing environmental conditions can cause multiple cycles of damage. Nevertheless, such changes may facilitate the use of crystallization inhibitors. When applied in the context of a fluctuating environment, inhibitors may have the potential to act as a holding measure, preventing the onset of crystallization for a sufficient length of time to allow environmental conditions to return to levels under which damage is not a threat. Furthermore, in some situations a delay in the onset of crystallization can allow mechanisms by which salt in solution is transported to proceed, such that crystallization takes place at the surface where damage is less severe. Indeed, this alteration of the transport properties of the salt-water system indicates that crystallization inhibitors could also be a useful adjunct to salt-reduction treatments to improve their extraction efficiency. This particular aspect is a focus for research by other partners in the Saltcontrol project.

In order to reduce the potential dangers associated with the use of inhibitors, we therefore need to know the extent and timescale of the fluctuations in RH and temperature that can occur without failure of the inhibitor. Previous work has shown that the speed of air movement is also an important factor in determining the rate of moisture loss from porous materials, and hence the time interval before the onset of crystallization and the type of damage caused.<sup>8, 9</sup> Therefore, airspeed also merits attention, together with RH and temperature, as an environmental factor that may affect the rate of salt damage.

### Salt supersaturation

Supersaturation of a salt solution, and ultimately damage, is caused by fluctuations in both RH and temperature. However, it should be stressed that changes in these two factors do not exclusively determine the onset of crystallization; the sizes of the pores, and the ways in which the pores are interconnected, may also play a significant role in precipitating crystallization.<sup>10</sup>

It is well known that the water-vapour pressure of a salt solution is strongly affected by its composition, and it has been shown that the presence of salt mixtures influences the rate of moisture uptake and loss by altering the difference between the ambient RH and vapour pressure of the solution.<sup>4, 11</sup> If crystallization is inhibited, the solution will continue to evaporate, and its water-vapour pressure will drop as it becomes increasingly supersaturated. Therefore, at constant RH and temperature, it is expected that the evaporation rate should fall as the difference in water-vapour pressure between the ambient RH and the salt solution decreases. Furthermore, at moderate levels of supersaturation, salt-crystallization inhibitors can delay the onset of crystallization indefi-



**Figure 4** Cleve Abbey, Somerset: the exterior of the sacristy and cloister viewed from the north, 1998.

nately, and so it is possible that a supersaturated solution can reach equilibrium with its surroundings at RH values below that at which crystallization would normally be predicted to take place. Thus, it appears that salt-crystallization inhibitors may help to reduce the incidence of salt damage in objects exposed to a fluctuating environment by slowing the rate of evaporation and extending the limits of environmental conditions under which damage does not occur.

The precise way in which changes in RH and temperature affect the kinetics of salt-solution supersaturation and crystallization in porous media has not yet been determined. Nor do we understand how this behaviour is mediated by the presence of inhibitors and their influence on the water-vapour pressure of the solution because of the promotion of higher levels of supersaturation. Also, it is becoming increasingly apparent – as our research at Cleve Abbey in Somerset (Figs 4, 5) suggests – that kinetics may play a significant role in determining not the only threshold supersaturation reached prior to crystallization, but also the pressure generated by the growing crystals, and, in the case of sodium sulphate, the identity of the crystalline phase that is formed.

## Conclusion

In our current work at the Institute we are addressing these issues in the hope that we will be able to clarify the dynamic nature of salt damage and the environmental conditions under which inhibitors, if found to be suitable for application in conservation, may be used. One of the aspects of crystallization inhibitors that makes them particularly attractive is that their potential use is not limited solely to a straightforward means of preventing salt crystallization. By delaying the onset of crystallization, so

that salts remain in solution in the object for longer, crystallization inhibitors have the capacity to enhance the effectiveness of salt-reduction treatments. Consequently, if the results of this study do show that inhibitors can be used successfully and reliably without risk to the object, they will increase the treatment options and will potentially offer enormous advantages for countering the notoriously difficult problem of salt damage.



**Figure 5** Detail of salt damage to part of a thirteenth-century wall painting on the south wall of the sacristy of Cleve Abbey, Somerset, 1997.

## Notes

1. A. Arnold & K. Zehnder, "Monitoring wall paintings affected by soluble salts", in *The conservation of wall paintings*, S. Cather (ed.), 103–136 (Los Angeles: Getty Conservation Institute, 1991).
2. J. Weber, "Salt-induced deterioration of the Romanesque wall paintings in the church of St. Georgen, Styria, Austria: a case study aiming at a better understanding of the behaviour of salt systems in ancient walls", in *Conservation of architectural surfaces: stone and wall coverings*, G. Bisconti & L. Graziano (eds), 97–103 (Venice: Il Cardo 1993).
3. C. Price & P. Brimblecombe, "Preventing salt damage in porous materials", *Preventive conservation: practice, theory and research*, R. A. Roy & P. Smith (eds), 90–93 (London: The International Institute for Conservation of Historic and Artistic Works, 1994).
4. The ECOS program makes it possible to predict the thermodynamic behaviour of soluble salt mixtures derived from the  $\text{Na}^+ - \text{K}^+ - \text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{NO}_3^- - \text{SO}_4^{2-} - \text{H}_2\text{O}$  system in relation to relative humidity and temperature. For further details see C. A. Price (ed.), *An expert chemical model for determining the environmental conditions needed to prevent salt damage in porous materials* [European Research Report 11, Technologies to Protect and Rehabilitate European Cultural Heritage] (London: Archetype, 2000).
5. A. Sawdy, "The role of environmental control for reducing the rate of salt damage in wall paintings", in *Conserving the painted past: developing approaches to wall painting conservation*, R. Gowing & A. Heritage (eds), 95–109 (London: James & James, 2003).
6. The project involves participating institutions from six European countries in addition to Belgium: Czech Republic, Germany, Greece, The Netherlands, Spain and the United Kingdom.
7. C. Rodriguez-Navarro & E. Doehne, "Salt weathering: influence of evaporation rate, supersaturation and crystallization pressure", *Earth Surface Processes and Landforms* **24**, 191–209, 1999.
8. R. Pender, *The behaviour of moisture in the porous support materials of wall paintings: an investigation of some environmental parameters*, PhD thesis, Conservation of Wall Painting Department, Courtauld Institute of Art, University of London, 2000.
9. See C. Rodriguez-Navarro & E. Doehne 1999 (n. 7 above).
10. A. Putnis, M. Prieto, L. Fernandez-Diaz, 1995, "Fluid supersaturation and crystallization in porous media", *Geological Magazine* **132**(1), 1–13, 1995.
11. A. Sawdy, *The kinetics of crystallization and deliquescence of some soluble salts found in wall paintings*, MSc thesis, Conservation of Wall Painting Department, Courtauld Institute of Art, University of London, 1995.